GPS Time Series Analysis of Southern California Associated with the 2010 M7.2 El Mayor/Cucapah Earthquake

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2011 EarthScope Meeting

QUAKESIM

Overview

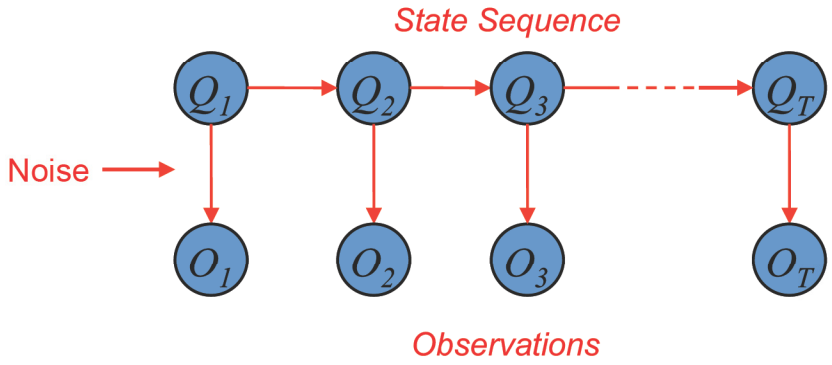
- The M 7.2 El-Mayor/Cucapah earthquake that occurred in Mexico on April 4, 2010 was well instrumented with continuous GPS stations in California
- Large offsets were observed at the GPS stations as a result of deformation from the earthquake providing information about the co-seismic fault slip as well as fault slip from large aftershocks.
- Information can also be obtained from the position time series at each station

Approach

- Want to understand the details of ground displacement as measured by GPS
- Use statistical, data-driven approaches rather than basing results on physical models
  - Avoids bias due to models
- Can be completely automated
- Do not answer science questions directly, but allow for identification of interesting behavior
  - We can define "interesting" in various ways

Hidden Markov Models

- Hidden Markov models (HMMs) allow us to segment GPS time series into discrete modes in order to extract information
  - Each mode corresponds to an underlying "hidden state" of a model
  - Described by the statistics of its member observations
- Can be done in the absence of labeled training data or other human supervision
  - Is entirely a data-driven approach
- Fitting a hidden Markov model in the absence of a priori information using the standard expectation-maximization (EM) method is a difficult problem
  - Presence of numerous local maxima in the objective function
- Address this problem through the use of the regularized deterministic annealing EM (RDAEM) algorithm
  - Produces stable, high-quality model fits
- Implemented this algorithm in the QuakeSim RDAHMM software package

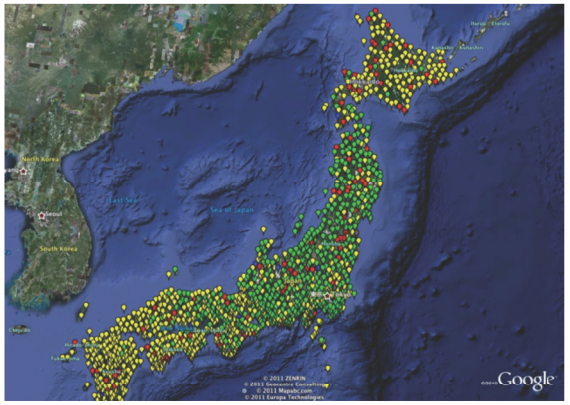


Data Source

- GPS daily position time series
- Produced by JPL using GIPSY
- Fit hidden Markov models (HMMs) to individual GPS time series
- Fitted HMMs allow segmentation of the GPS time series into discrete modes
- The geographical distribution of state changes among GPS stations provides insight into the geophysical processes of the region
- Solutions available for different data sources at
  - http://quakesim.org/portal/timeseries

An Example: Japan Time Series Analysis

March 11, 2011 0500 UTC



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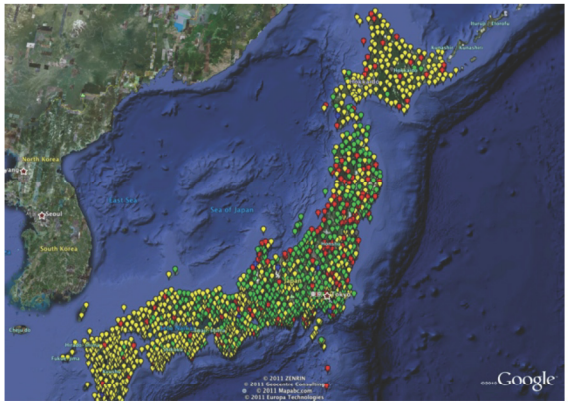

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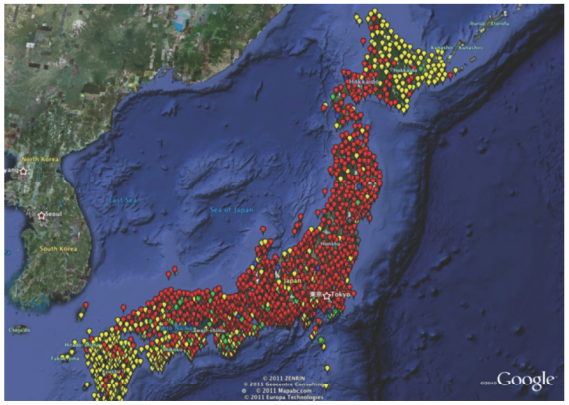

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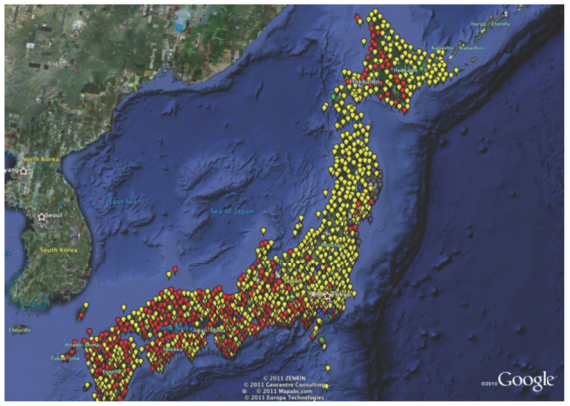

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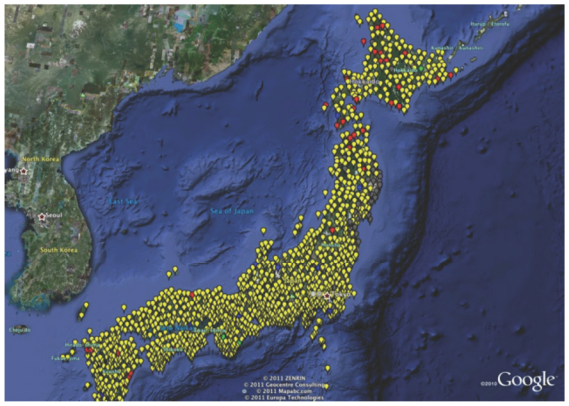
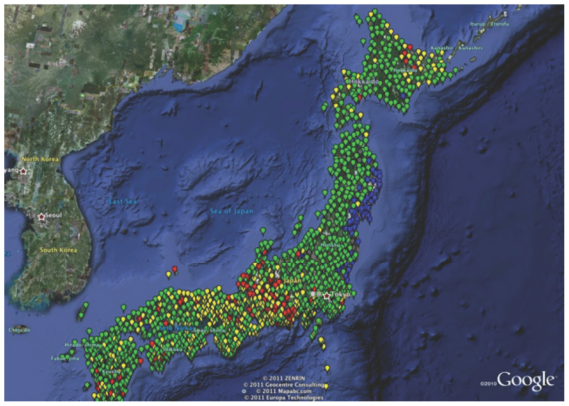
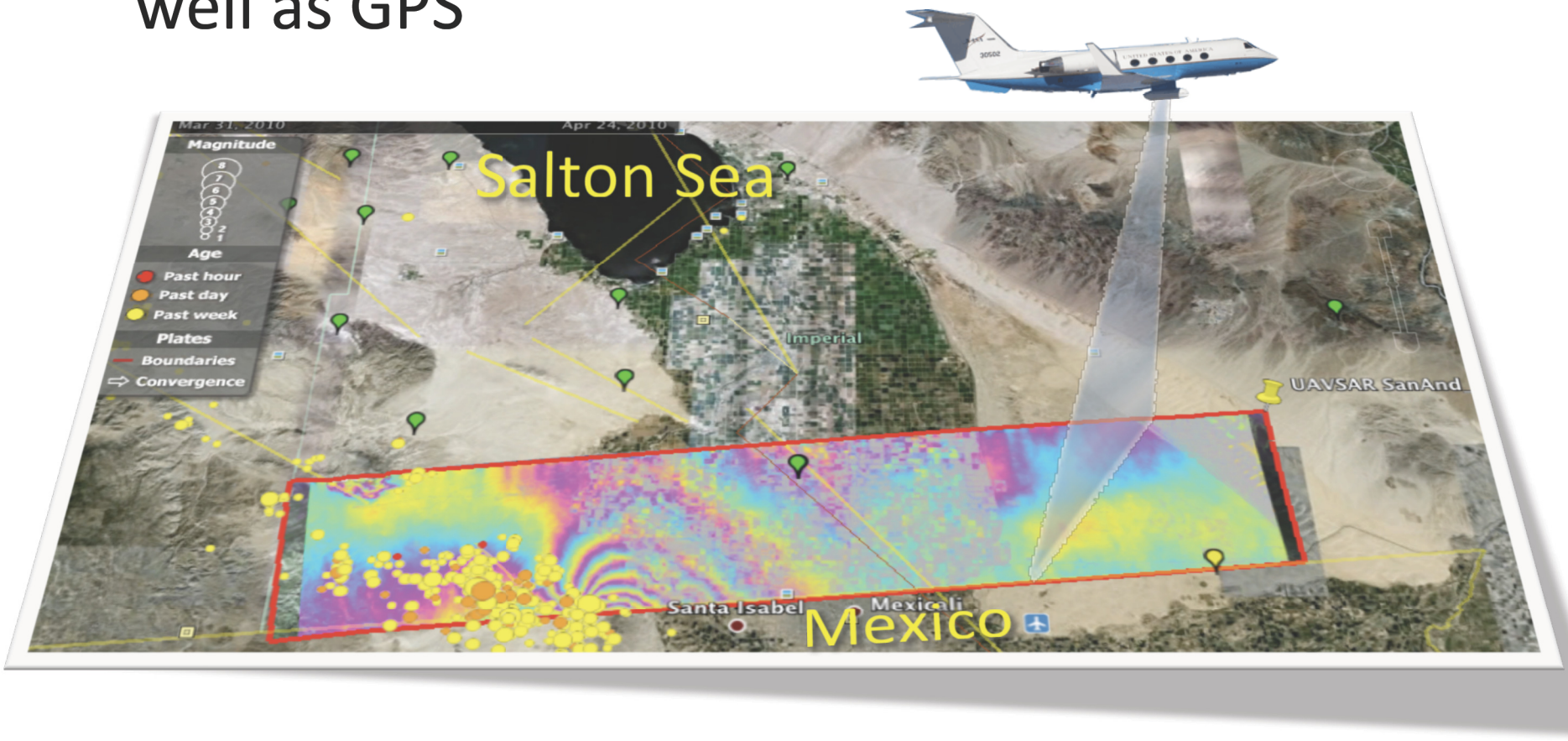


March 13, 2011 1300 UTC

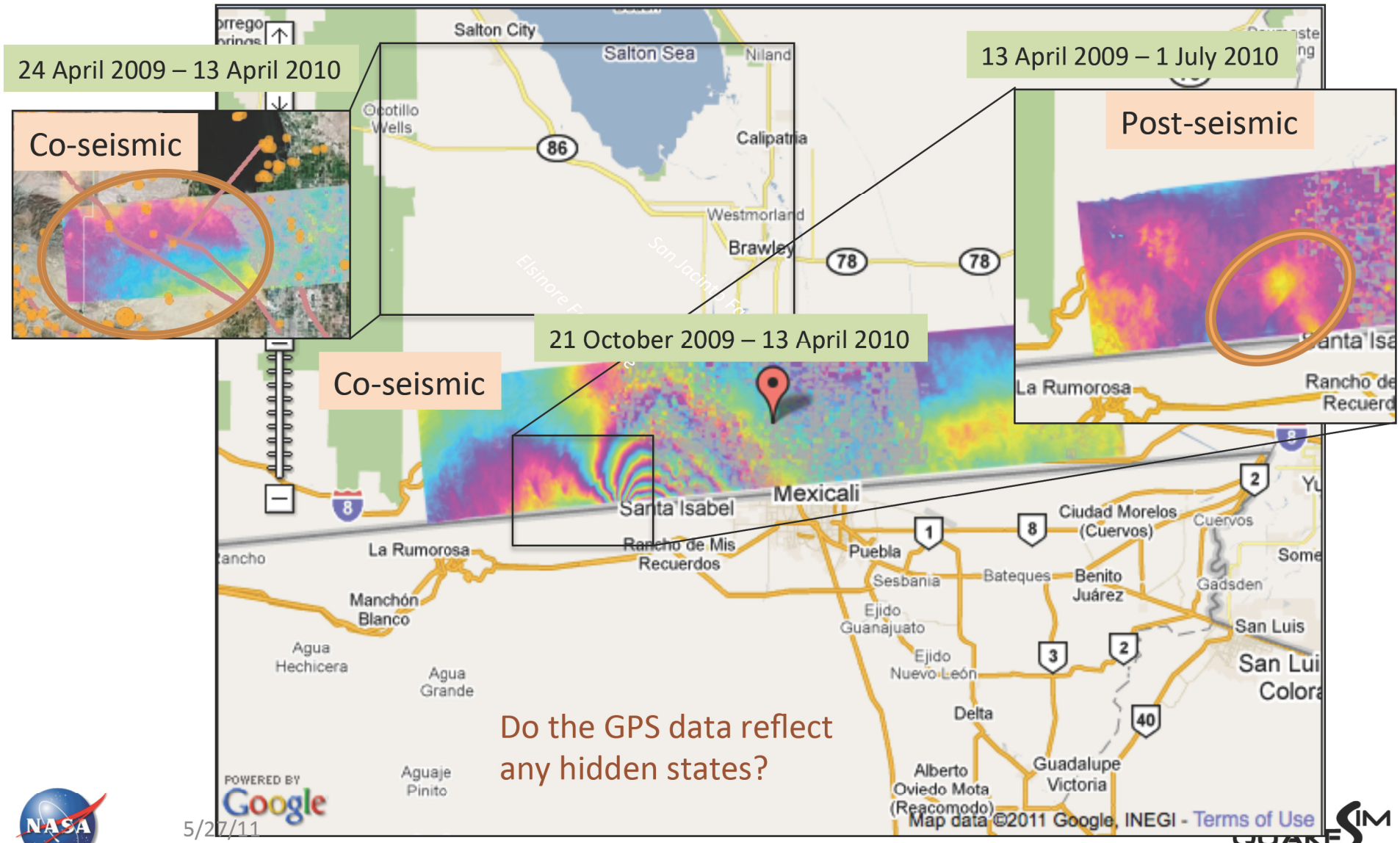


2010 El Mayor-Cucapah Earthquake

- The earthquake was observed with UAVSAR as well as GPS



UAVSAR Indicates Triggered Slip on other Faults



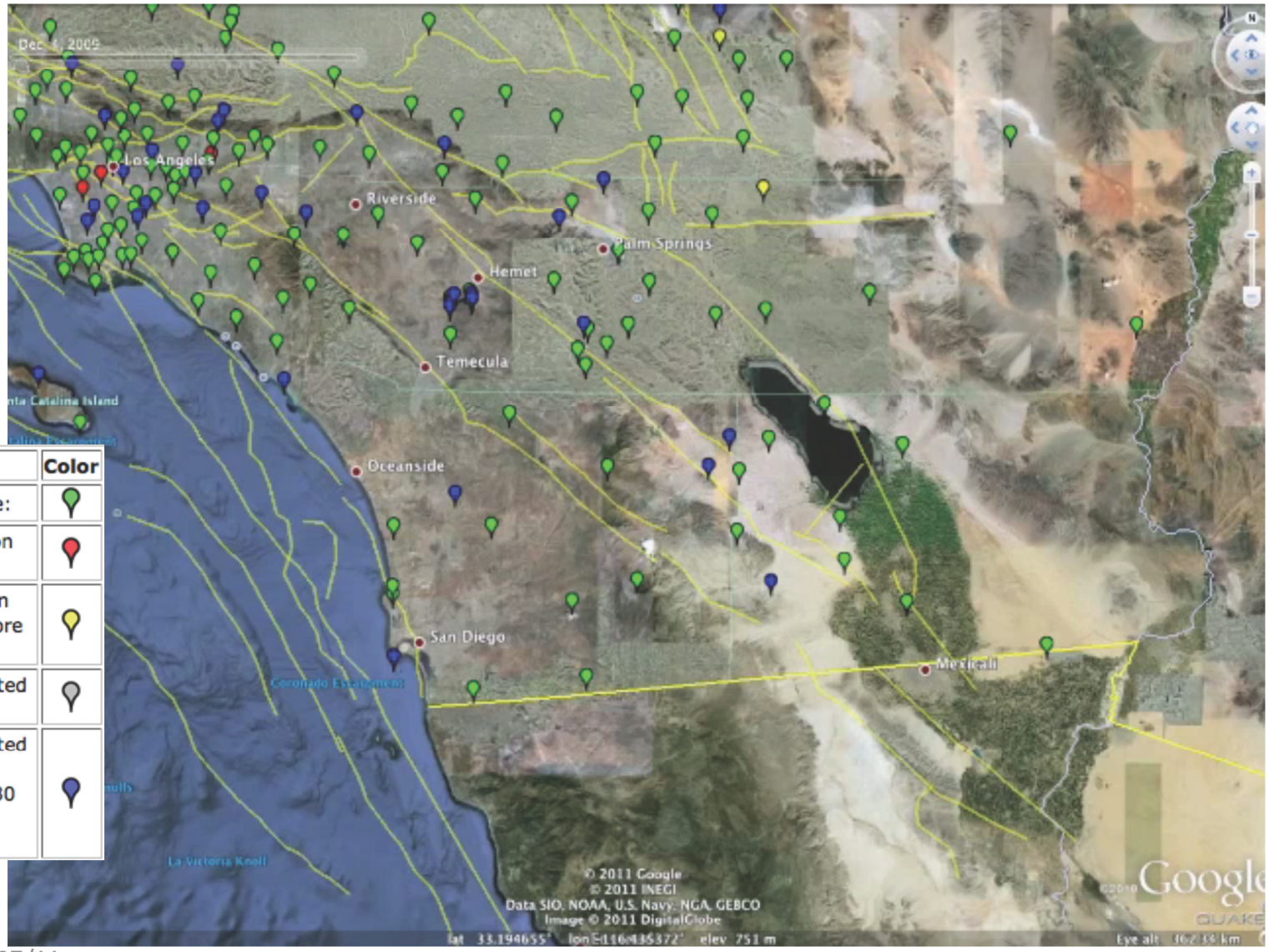
Do the GPS data reflect any hidden states?

El Mayor-Cucapah Earthquake

GPS Time series analysis

- Did something happen north of the rupture in the week before the earthquake?
- Can explore data sets and analysis results on both
  - micro-scale (individual station)
  - macro-scale (whole network)
- Users can
  - focus in on or scroll through particular spatial or temporal time windows
  - observe dynamic behavior by created movies that display the system state
- RDAHMM results are available through the QuakeSim web portal
  - http://quakesim.org/portal/timeseries

GPS States Surrounding the Earthquake



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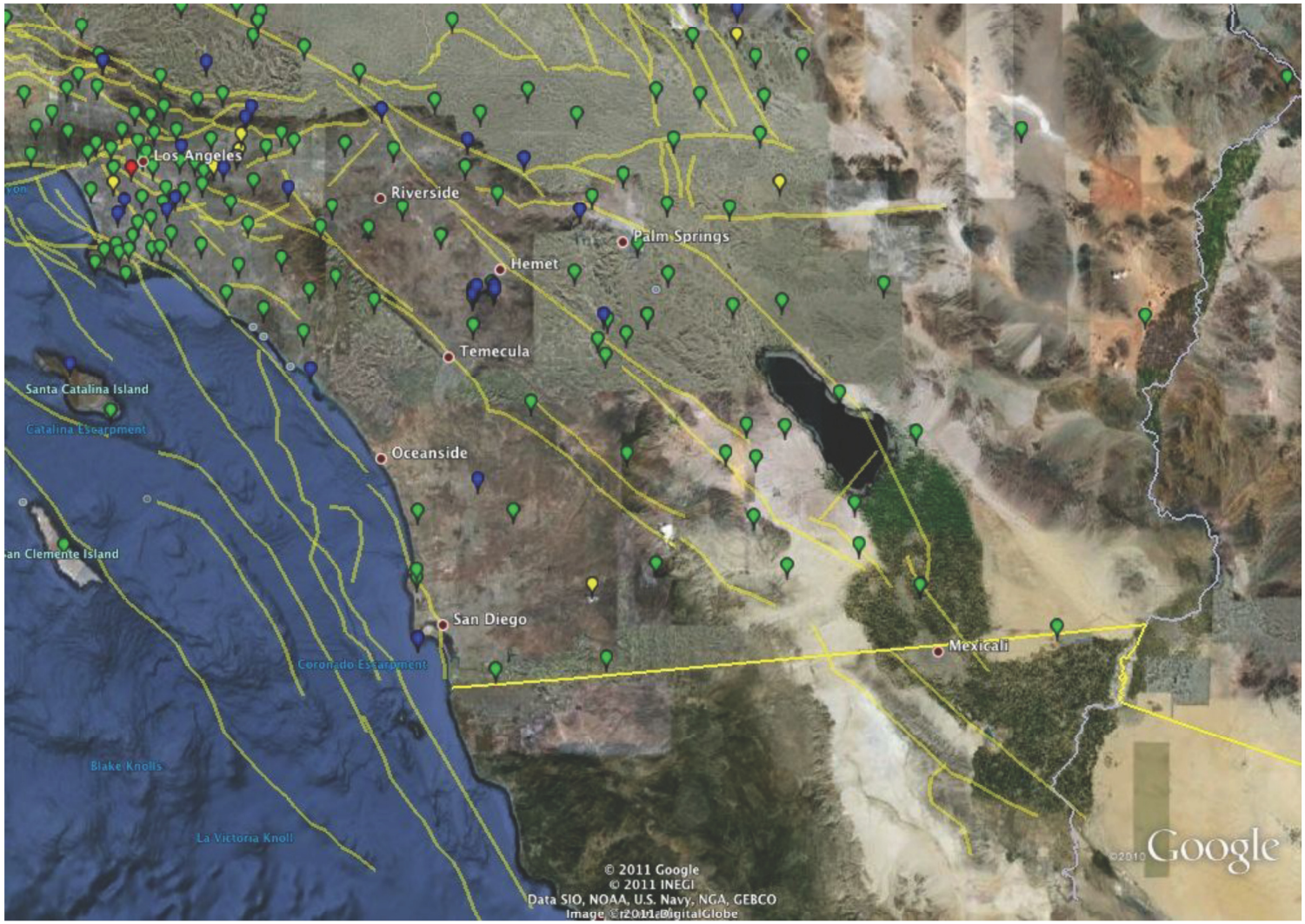
2010-03-27: T-8



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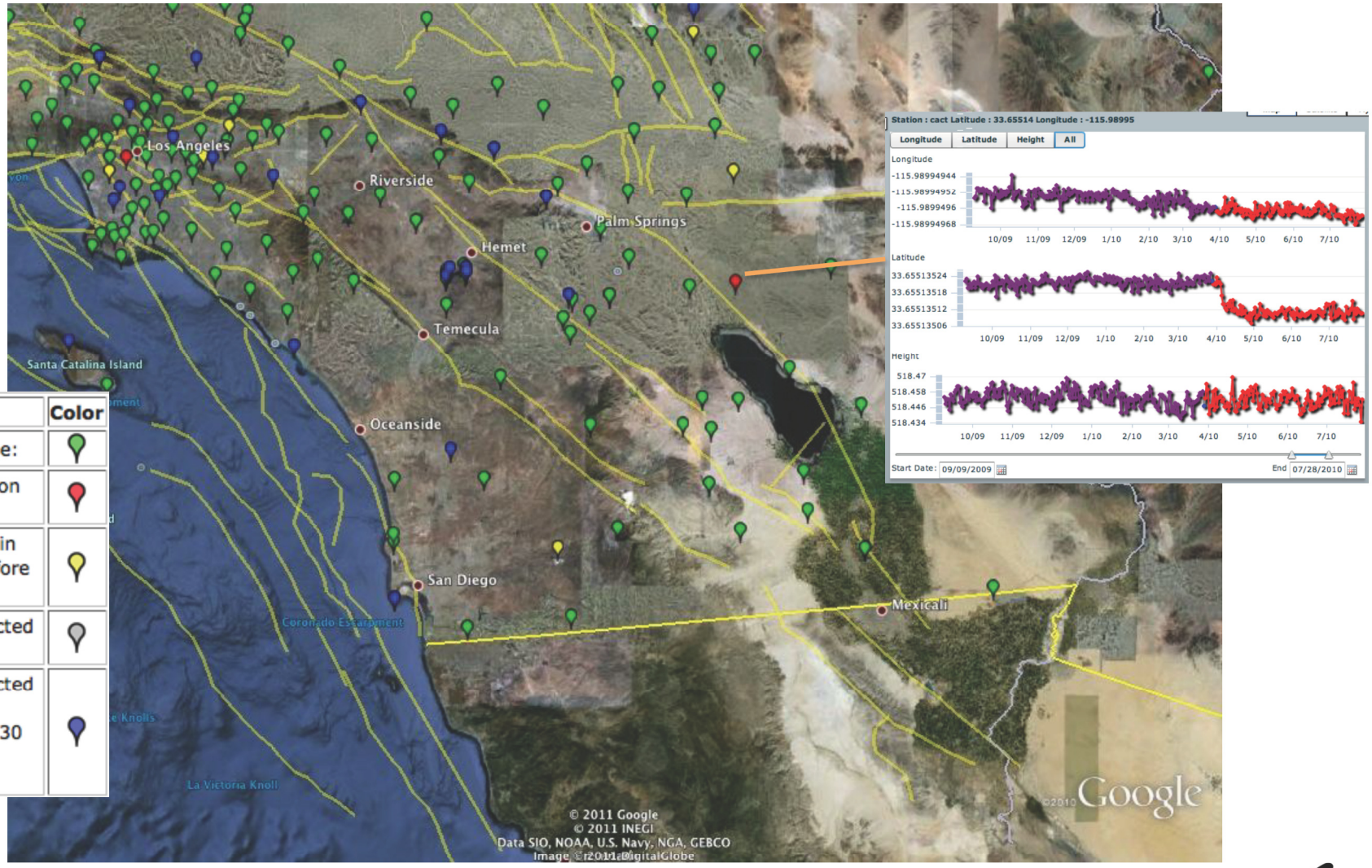

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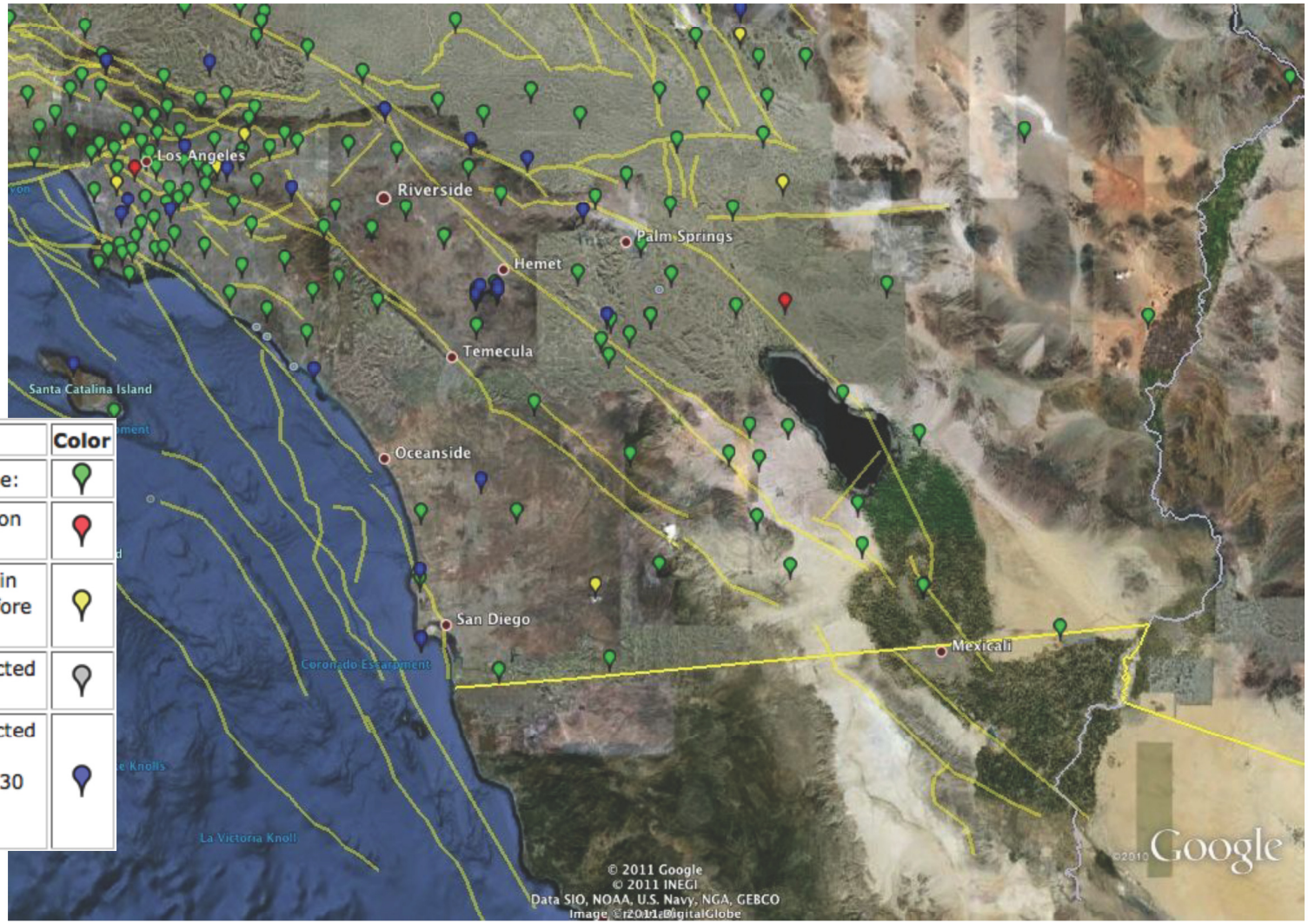
2010-03-29: T-6



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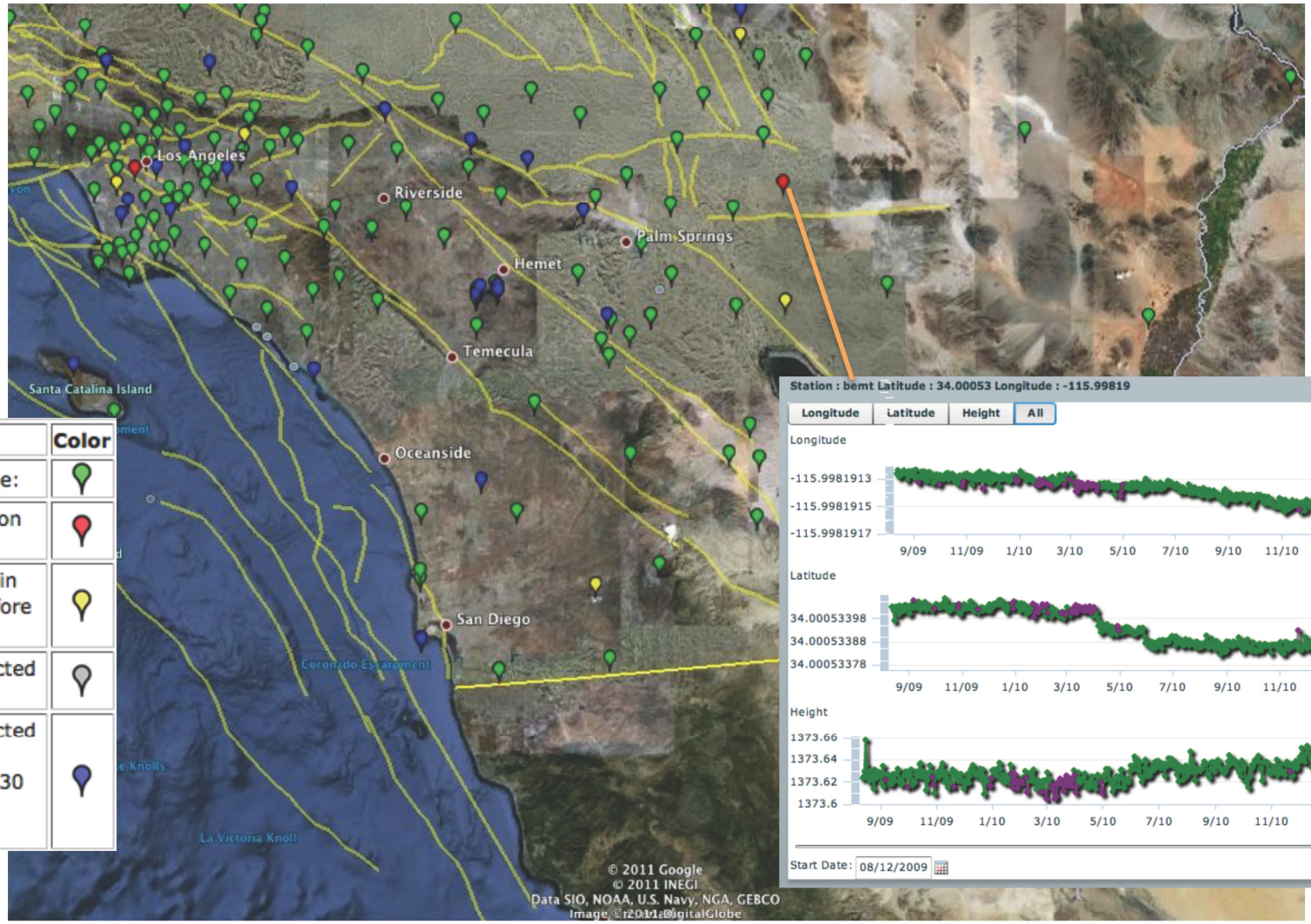

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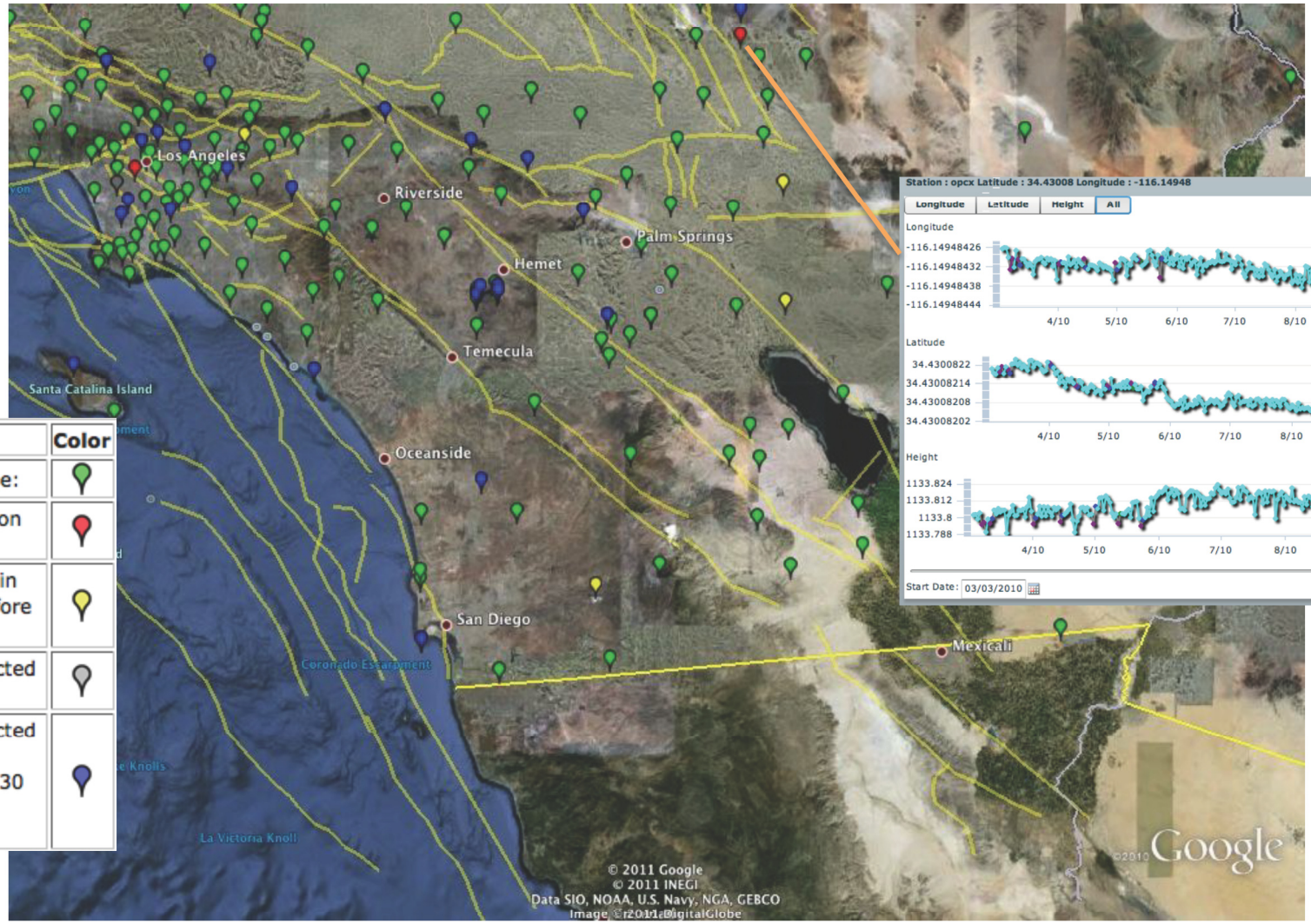
2010-04-01: T-4



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Time is UTC

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2010-04-02: T-3

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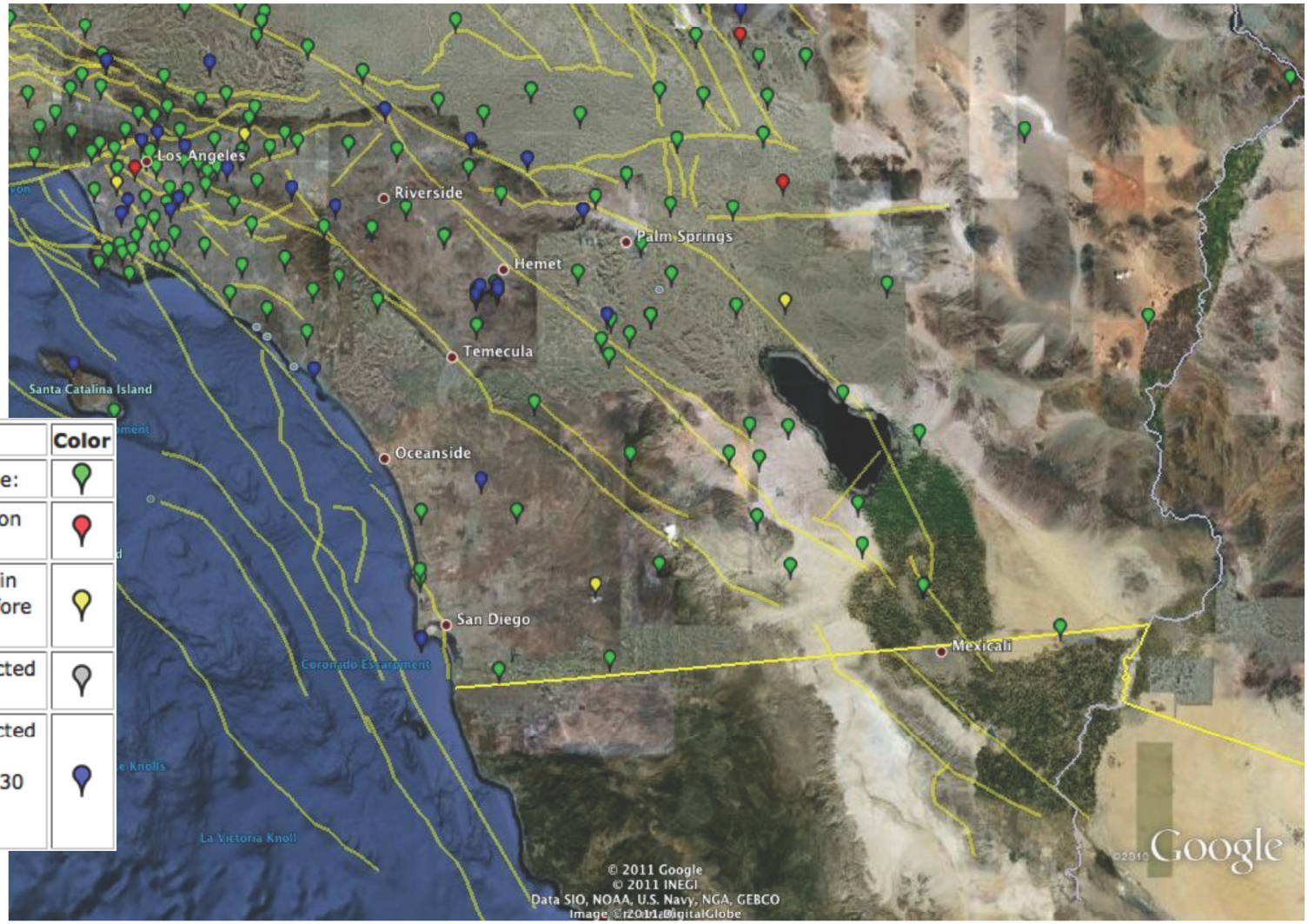
2010-04-03: T-2



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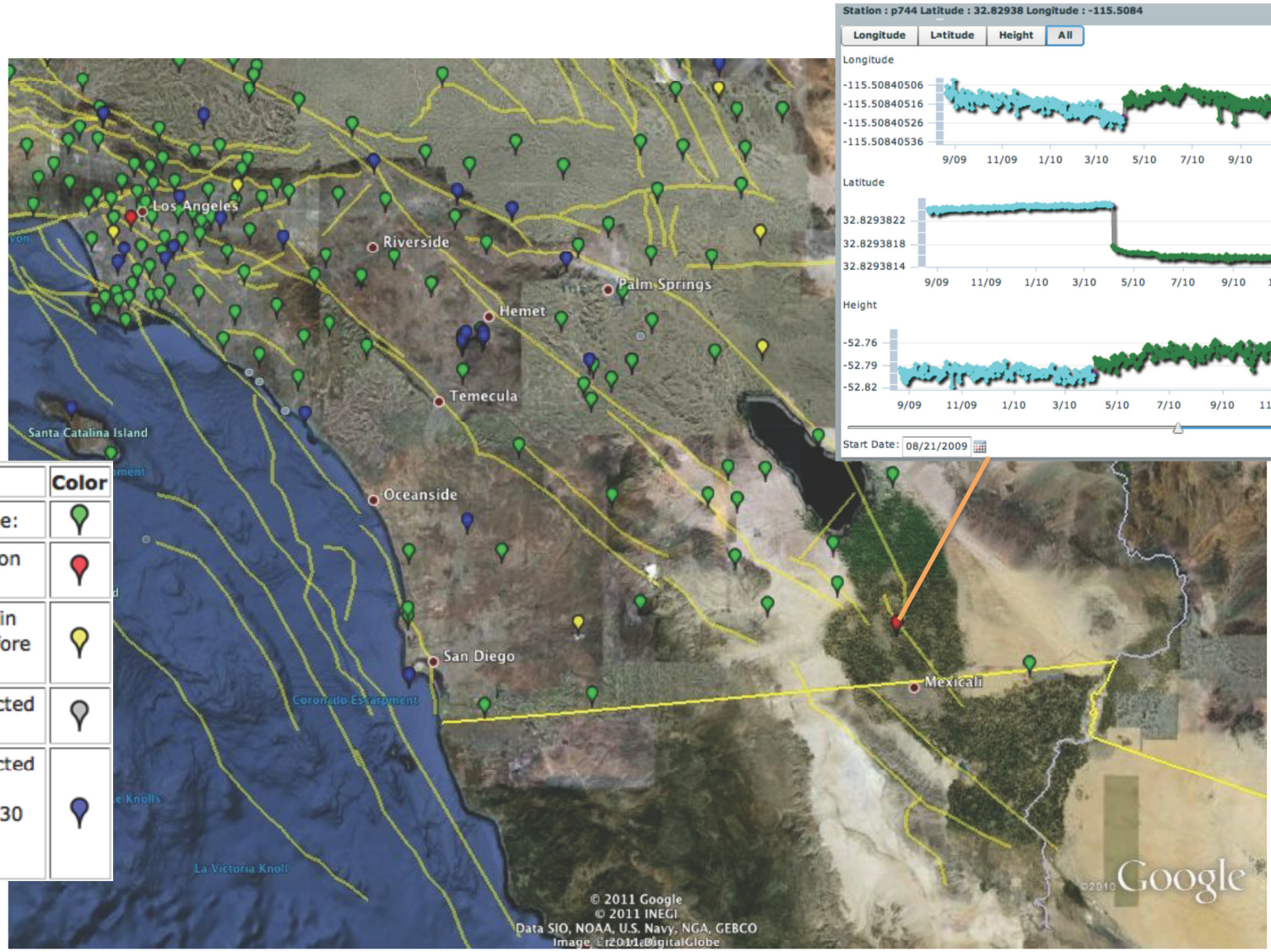
2010-04-04: T-1



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Time is UTC

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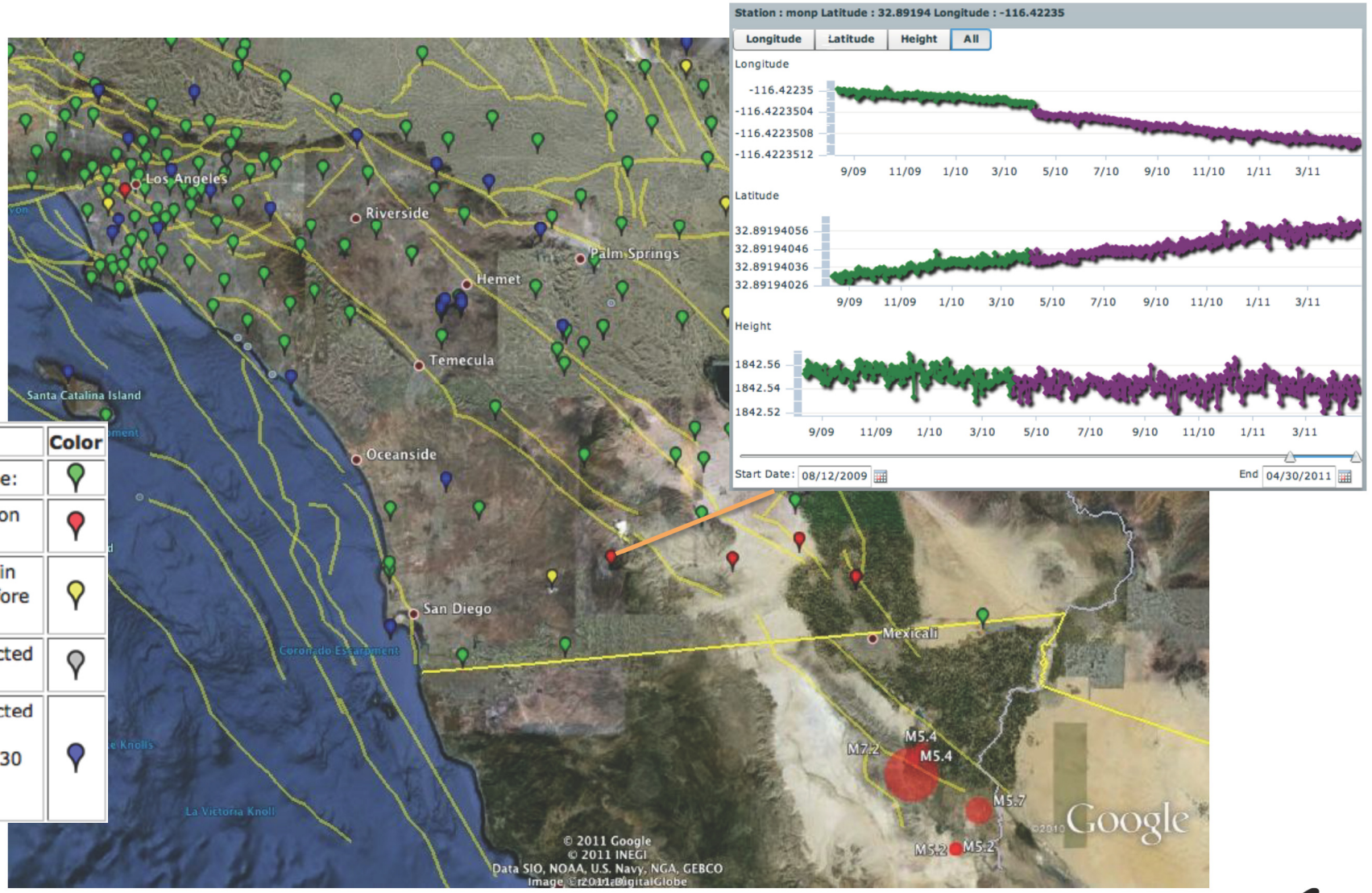
2010-04-05: T-0



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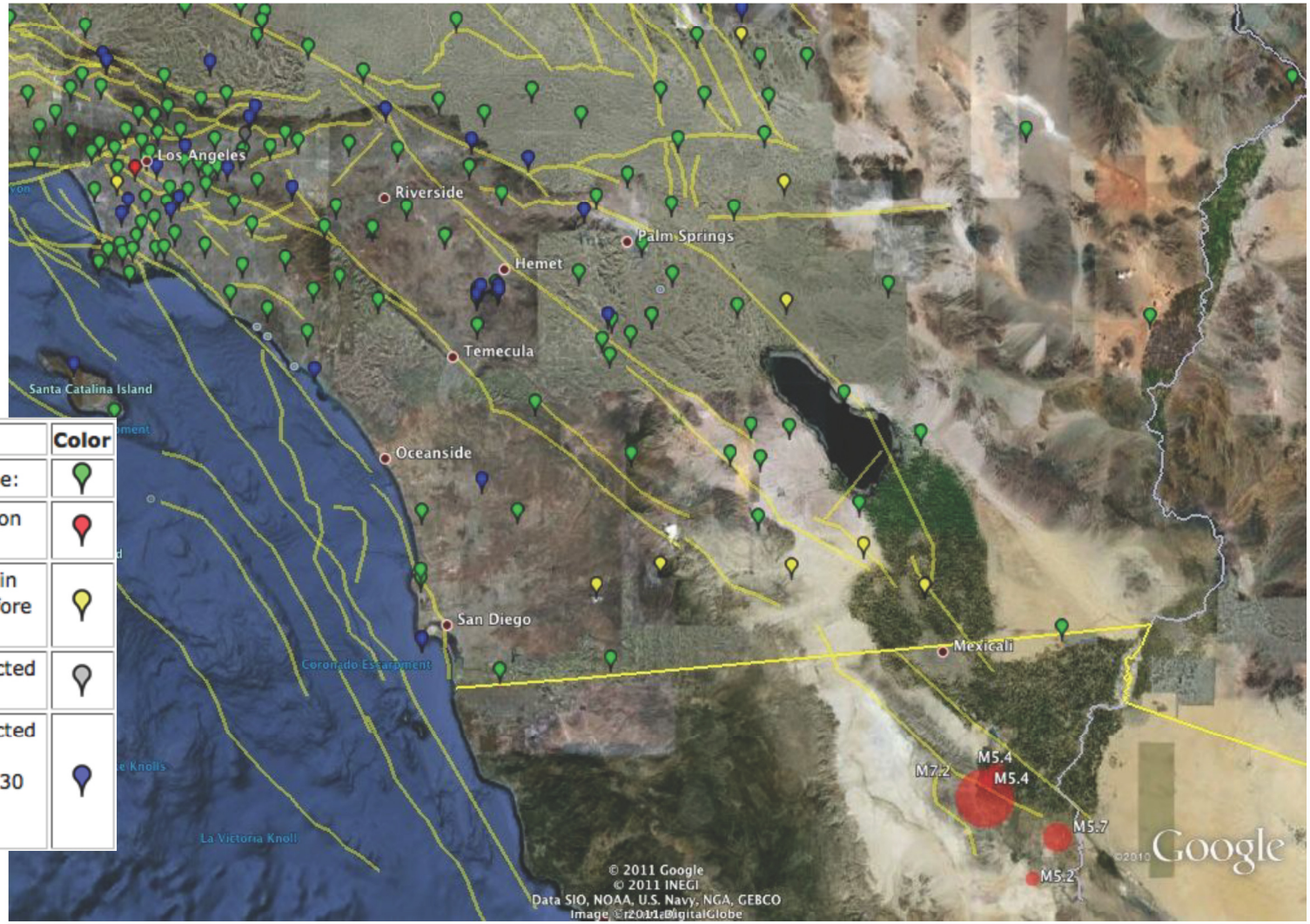
Time is UTC

2010-04-06: T+1



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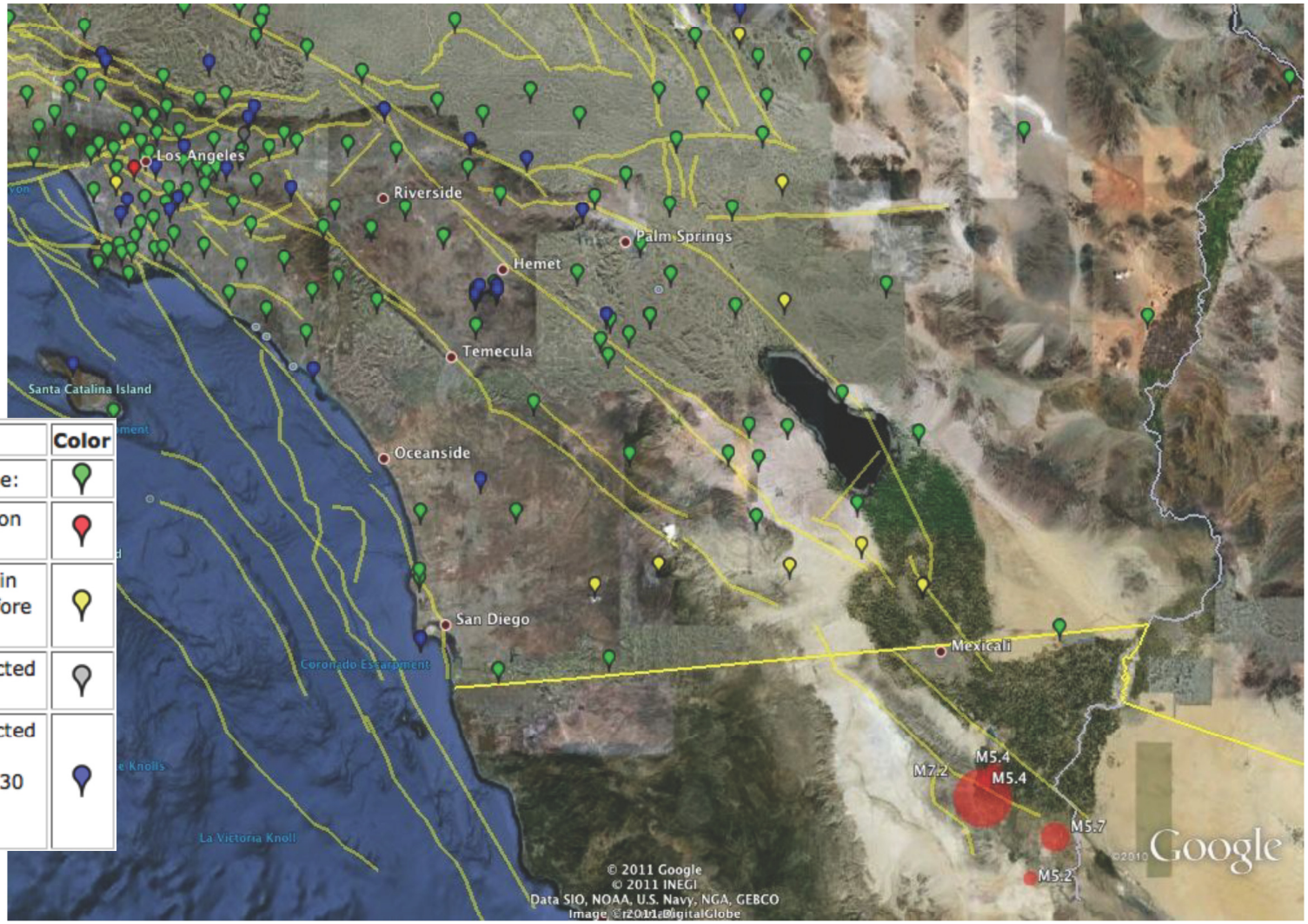
2010-05-07: T+2



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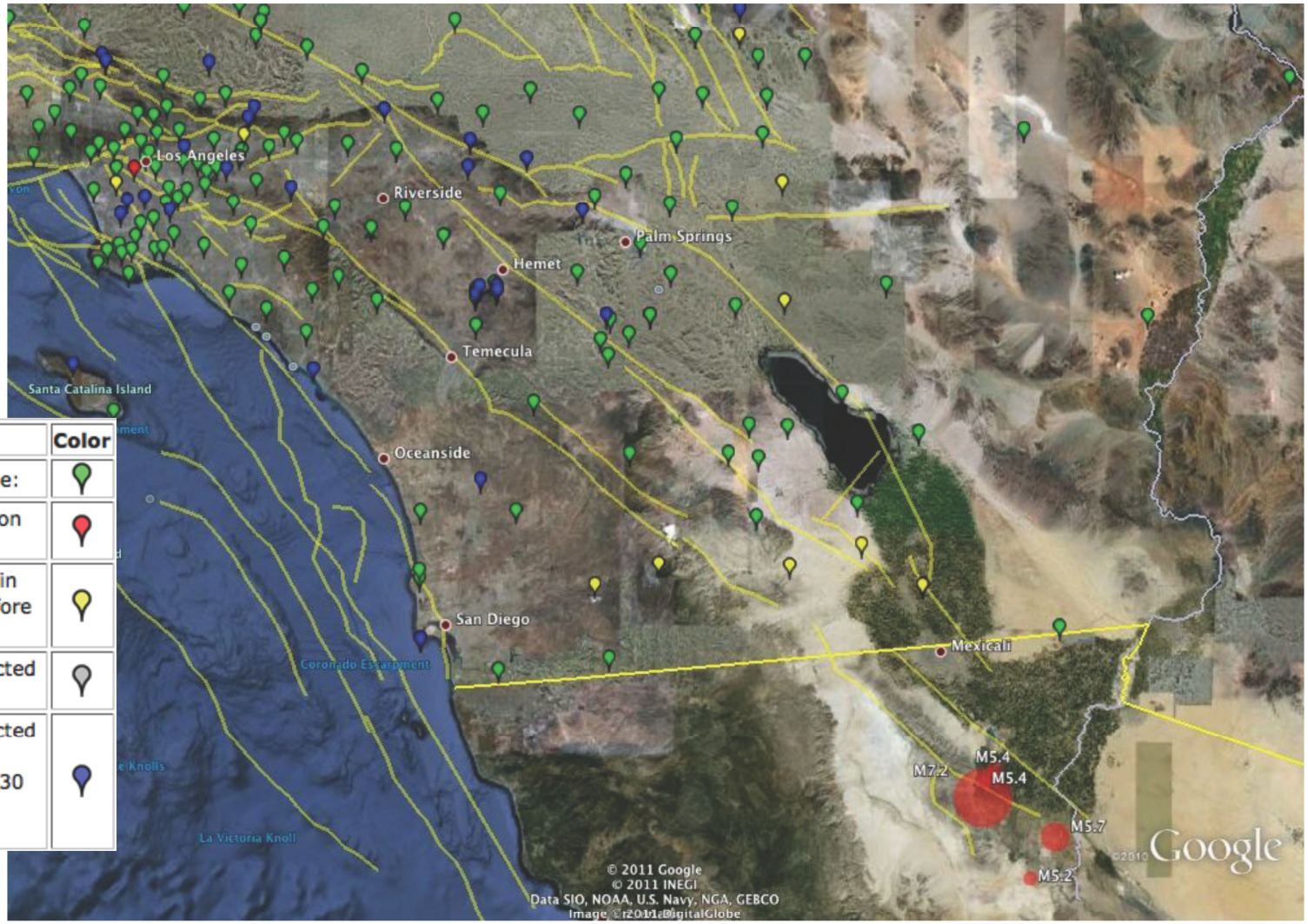
Time is UTC

2010-05-08: T+3



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Time is UTC

2010 El Mayor-Cucapah Earthquake

- Analysis of time series data around the 2010 El-Mayor/Cucapah earthquake shows that GPS stations change state near the rupture as expected
- GPS stations also change state farther from the rupture, but near other faults, such as the San Andreas and San Jacinto faults
- The GPS stations that change state associated with the earthquake tend to be in close proximity to faults that exhibited creep events associated with the earthquake in Baja

Using Covariance Descriptors

- We can calculate the so-called "divergence" between two time series using the generalized covariance distance metric [Tuzel 2008]:

$$\rho(C_1, C_2) = \sqrt{\sum_{i=1}^{m} \ln^2 \lambda_i(C_1, C_2)} \quad \text{for } x_j C_1 = \lambda_j x_j C_2$$

- Because the metric is based on the time series statistics, we can easily compare time series of different lengths
- To find anomalies, we compare sub-windows of individual GPS time series with a "training set" from that same time series that contains nominal behavior
- Windows with a high divergence indicate anomalous activity as compared to the normal behavior of the station